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AN ELECTRO-OPTIC, HIGH-VOLTAGE,
TRANSIENT PROBE

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I. INTRODUCTION

Fast discharge laser diagnostics require transient differential high voltage (10 to 20 kV, 10 to 50 ns) measurements (ref. 1). The high currents needed for charging and firing the laser produce serious ground loop voltages and radiate severe electromagnetic interference. The probe described herein was developed to overcome these measurement problems and was prompted by noting the successful application of an electro-optic current transducer (ref. 2). That technique was modified for high voltage measurements. Interference reduction and common mode rejection techniques were also applied in development of the probe.

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Commercially available probes are single-ended. Used in differential pairs, they could never be balanced adequately, and the difference amplifiers could not be isolated well enough from interference of the discharge. Fast, single-ended, high voltage probes are described in the literature (ref. 3) but these are of lower impedance and the difference amplifier problems exist again when the probes are used in differential pairs. There is only one case described in the literature (ref. 4, a Kerr-cell transducer) that attempts a floating high-voltage measurement of the discharge in a fast laser. It was not applied because of the complicated apparatus required and difficult data processing of the resultant signal. The probe developed herein proved to be less noisy, less affected by interference and ground loops, and easier to calibrate, with no day to day trimming required.

The authors are indebted to J. R. Hoge for his help in fabricating the probe system. We are especially grateful to C. P. Wang and H. Mirels of Aerospace Corporation for their assistance and helpful discussions in building the fast discharge apparatus.

II. DESCRIPTION OF INSTRUMENT

The electro-optic h. v. probe system shown schematically in figure 1 provides oscilloscope measurement of transient voltages of up to 20 kV peak. The probe was designed for direct connection across the floating electrodes of a Blumlein line discharge apparatus, near the discharge region. An exploded view of the probe is shown in figure 2.

A small probe size was required because of space limitations imposed by the discharge apparatus geometry and for fast dynamic response. The probe components were mounted on a vector board and assembled in a lucite enclosure measuring 5.56 by 3.81 by 3.81 cm. The lucite enclosure and exposed sections of the fiber optics cable were painted black to protect the optical system from stray light emanating from the intense discharge as well as from ambient light.

To minimize susceptibility to electromagnetic interference (EMI) caused by the discharge apparatus and associated h. v. electronics, the photomultiplier tube (PMT), the PMT power supply, and oscilloscope (CRO) were remotely located in a shielded room as shown in figure 1. The PMT was a type 9658-R, a 50-mm end-on tube with extended S-20 spectral response and a 10 ns risetime. A CRO having a vertical amplifier risetime capability of 3.4 ns and high visual brightness was used. An 8-meter length of plastic clad silica fiber (ITT type PS-05-10) served as a single fiber transmission cable to couple the light emitting diode (LED) optical signal to the shielded room. Spectral attenuation of this fiber is near minimum (12 dB/km) at the 655 nm peak wavelength of red light radiated by the LED (HP type 5082-4880). The fiber optics cable was routed to the shielded room in a single notched wooden tray system having removable covers for access.

Because of high voltage hold-off and low inductance package requirements, as well as limited space on the vector board, probe resistor R1 was of a special design. In addition, resistor R1 was designed for low shunt capacitance to preclude leading-edge overshoot at the probe output. The calculated shunt capacitance of R1 was approximately 1 pf. This resistor, which limits the peak current through the LED, was a water-filled glass unit fabricated from 9 mm o. d. by 31.8 mm long standard wall glass tubing. Two platinum discs 0.2 mm thick by 6.3 mm diameter and separated by 20.6 mm acted as resistor electrodes. Each electrode was supported by a 0.63 mm diameter tungsten rod to which a stainless steel sleeve was silver soldered for electrical connections. A 2 mm o. d. standard wall glass tube was formed to the center of the glass assembly. This served as a fill tube which was later pinched off to give a sealed resistor assembly.

A resistance in the range of 20 to 30 k Ω was obtained with this design, using tap water, limiting the peak current through the LED to a maximum of 1 ampere with a peak transient voltage of 20 kV across the discharge electrodes. The resistance was constant over the full 20 kV input range for a 6.5 μ s pulse.

A small amount of forward bias current through the LED resulted in a probe output for low amplitude reversed-polarity transients. A forward bias of 14 mA was chosen for the probe. Resistor R2 shown in figure 1 limits the forward bias current set by potentiometer R3. To minimize the effects of EMI pickup on the LED bias input leads, R2 was included in the probe instead of with other external bias circuit components. When low amplitude reversed-polarity transients are not of interest, the probe design permits nonbiased operation of the LED by simply disabling or disconnecting the bias circuit.

To reduce interference due to circulating ground-noise currents and noise pickup from adjacent leads between interfacing circuits, a balun or common-mode choke was included in series with each shielded cable, as shown in figures 1 and 2. A balun is a

bifilar wound, broadband transformer that can substantially reduce this type of interference (ref. 5). Each balun was of simple construction, with 6 to 10 turns of coaxial cable looped through a commercially available torroid ferrite core easily giving the bifilar configuration.

III. CALIBRATION METHODS

Ideally, output calibration and dynamic response measurements of the probe system require a pulse generator with output adjustable to 20 kV, pulse width of 100 ns or less, and risetime better than the LED speed of response (15 ns). Some compromise of these requirements was necessary to utilize available test equipment. Initially, a 1:10 step-up transformer was used during calibration to boost the output of a 0 to 2 kV pulse generator rated at 30 ns risetime. However, this was unsuitable for dynamic response measurements because of severely increased risetimes, on the order of $2.5 \mu\text{s}$ due to reflected transformer capacitance. A second setup, suitable for dynamic response measurements, used a power amplifier delivering up to 10 kV output with 40 ns risetime when driven by the 2 kV pulse generator. Probe input for both cases was measured using a precision commercially available 1320:1 capacitive divider.

IV. CALIBRATION RESULTS

Typical traces taken during initial pulse calibration, using a 1:10 step-up transformer, are shown in figure 3. The PMT power supply was adjusted to give a probe output of 15 mV with a probe input of 10 kV and 14 mA of forward bias. The PMT supply was then held constant (910 V) throughout the remainder of the calibration. It will be noted that most of the low amplitude reversed-polarity oscillation on the undershoot of the input pulse was faithfully reproduced at the probe output, due to the 0.4 mV offset resulting from forward bias. The probe calibration plot, shown in figure 4, is essentially linear and overlapping for both the zero bias and 14 mA bias cases. The slight deviation from linearity at higher voltages is due to a combination of the PMT nonlinearity and the nonlinearity of the luminous intensity vs forward current characteristic of the LED.

The probe system and pulse generator were relocated for the dynamic response measurements, so that an available but cumbersome power amplifier could be used. A new fiber optics cable was prepared expressly for this application, so that the existing cable would not be jeopardized by the move. Typical traces taken during this measurement are shown in figure 5 for a 10 kV input pulse. An input risetime of 40 ns (fig. 5(c))

is preserved by the probe (fig. 5(d)); however, the pulse width is broadened or stretched approximately 10 ns by the probe. The pulse stretching was tolerated for the intended use of the probe. Noise from the LED and PMT is seen as aberrations on the probe output. Since equal output amplitudes (figs. 5(b) and (d)) were obtained from either the wide or narrow input pulse (figs. 5(a) and (c)), the calibration curve of figure 4, obtained with a wide input pulse, is valid and useable for narrow pulse work as well.

V. APPLICATION OF THE PROBE

Two of the new probe systems were used on a fast discharge apparatus. This apparatus is a Blumlein discharge device used in the nonwave mode and similar to that described in reference 1. One of the probe systems was used to measure the voltage across the Blumlein spark gap as it was pulse charged and fired. The other probe system was used to measure the floating voltage across the laser discharge electrodes of the Blumlein device.

A typical set of waveforms obtained are shown in figure 6. Figures 6(a) and (b) are traces taken simultaneously with 500 ns/cm sweep for one shot of the apparatus. The pulse charge reached 15.0 kV before the trace shows that the spark gap fired (fig. 6(a)). The charging occurred almost linearly for 750 ns. Figure 6(b) shows that the laser discharge voltage is a very short duration, 9.8 kV pulse voltage.

Figures 6(c) and (d) are traces taken simultaneously with 50 ns/cm for another shot of the apparatus. The traces are started to record events near spark gap firing time T_{00} . The pulse charge reached 15.3 kV before the spark fired as can be seen in figure 6(c). The fast sweep trace (fig. 6(c)) also shows detail after the spark gap fired. About 25 ns after the spark gap fires, the spark gap voltage recovers slightly due to the influence of the laser discharge initiation. Figure 6(a) shows that at about 150 ns after the spark gap fires, some low frequency ringing voltage is detected. The pulse charging system is interacting with the discharged Blumlein system. This is not of importance since the laser discharge pulse is completed by then.

The laser discharge voltage (fig. 6(d)) is seen as a 30 nsec, FWHM, 9.8 kV amplitude pulse, with a risetime of 25 nsec. The goal of the new probe research was to obtain a trace of this quality under the high noise environment of the Blumlein apparatus.

The new probe system signal was also compared with the signal from a differential pair of commercial resistive probes. Both probe systems were used to measure the spark gap voltage simultaneously. Figure 7 shows these comparison traces for both a shot at slow (500 nsec/cm) and a shot at fast (50 nsec/cm) sweep.

Comparing figures 7(a) and (b), one limitation of the new probe system is noted, namely only unipolar signals can be detected. Large amounts of bias to offset the detector might be thought of as a solution to this limitation. This is not possible, however, because prolonged high current will destroy the light emitting diode, if DC bias is chosen. Pulse bias is also found to be impractical due to excessive noise incurred by the bias summing technique.

In other respects, the new probe system is less noisy, less affected by trace intensity modulation, has reduced ground loop errors and is easier to calibrate. Figures 7(c) and (d) show clearly dynamic advantages of the new probe system. In figure 7(d) there is uncontrolled intensity modulation, due to the proximity of the oscilloscope to the apparatus enforced by commercial probe integral cables. The unwanted noise pickup and modulation make barely intelligible and distorted signals. These limitations make the successful use of commercial resistive probe systems impossible if that technique is used to measure laser discharge floating voltage.

The new probe system can be used in any application wherein the voltage pulse has greater than 30 nsec risetime and can tolerate 25 k Ω probe input impedance. If better detectors are available, or additional PMT noise can be tolerated, or multi-fiber optical transmission cable is used, the probe can be simply redesigned for higher input impedance. Amplitude error of the present work was limited by the readability of the recording film and the oscilloscope to approximately 7 percent. For repetitive pulses the system has been successfully operated with a duty cycle of 7×10^{-5} , the limiting duty cycle of the light emitting diode being 3×10^{-4} for a one ampere peak pulse through the diode.

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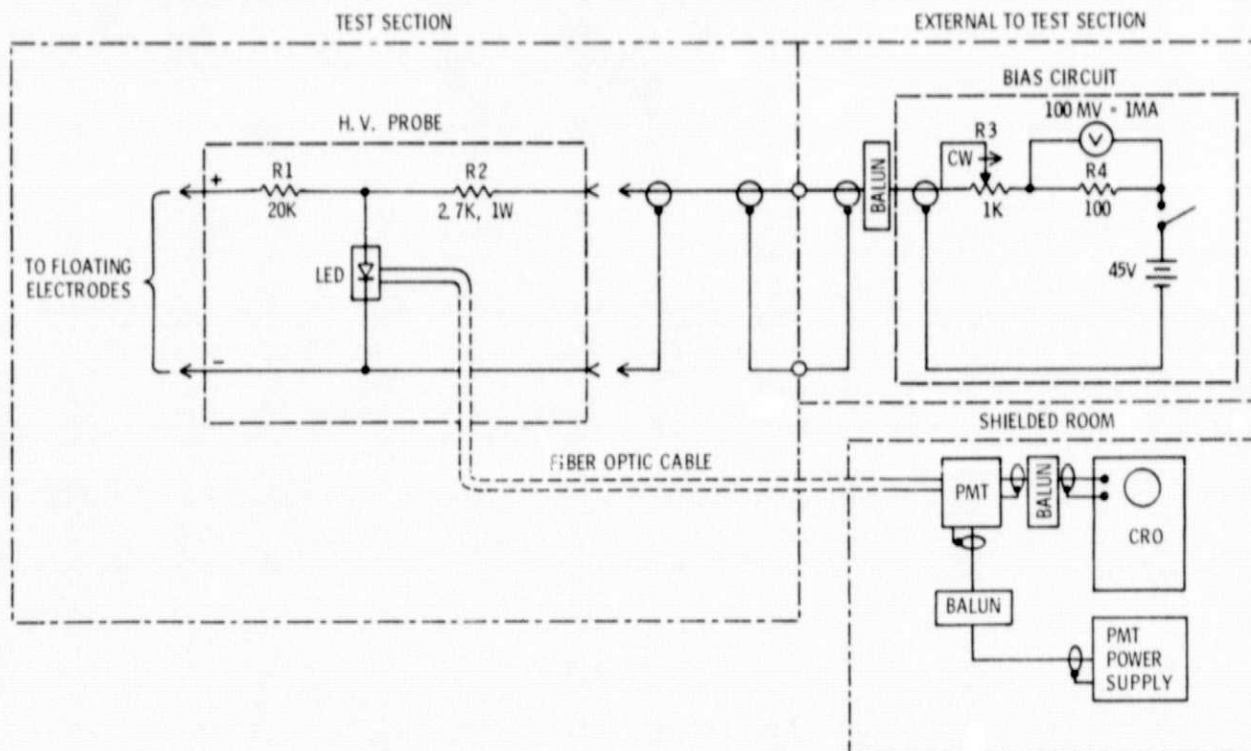
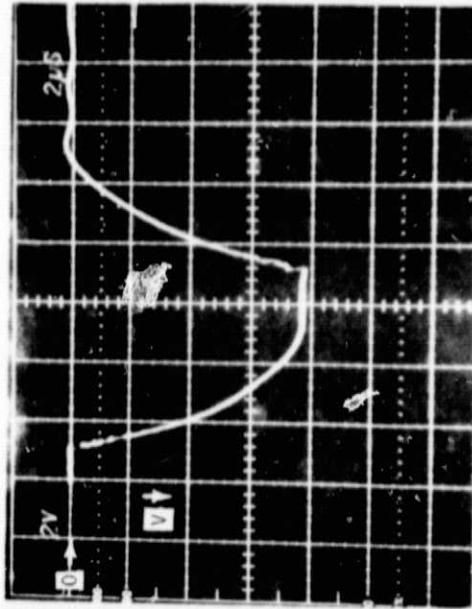
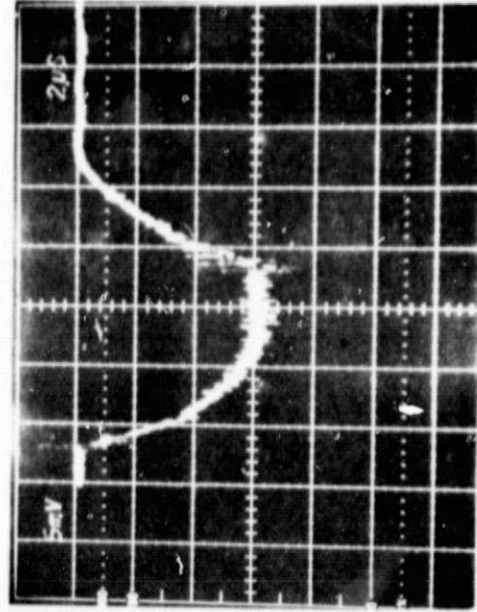


Figure 1. - Schematic Diagram of Electro-optic H. V. Probe System.

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(a) PROBE INPUT MEASURED WITH 1320:1 capacitive divider.



(b) ELECTRO-OPTIC H. V. PROBE OUTPUT.
Figure 3. - Typical traces during initial calibration.

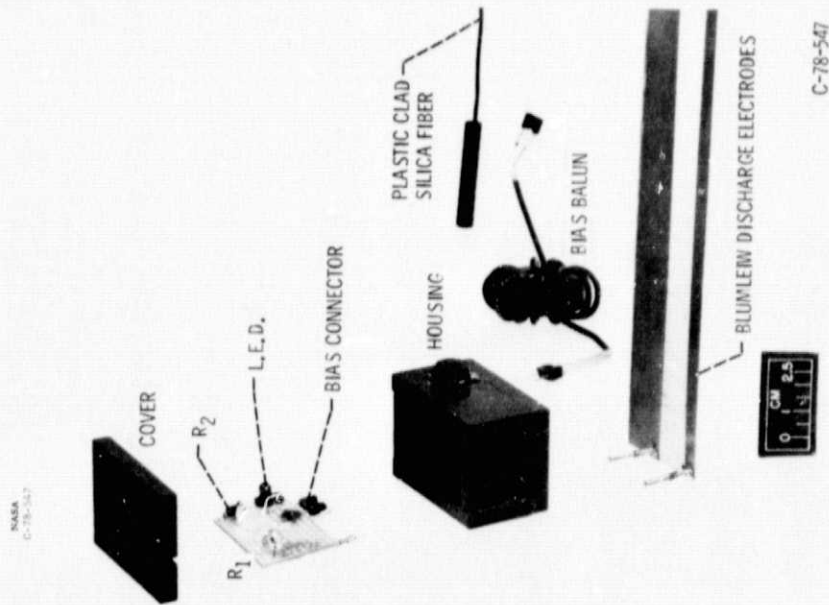
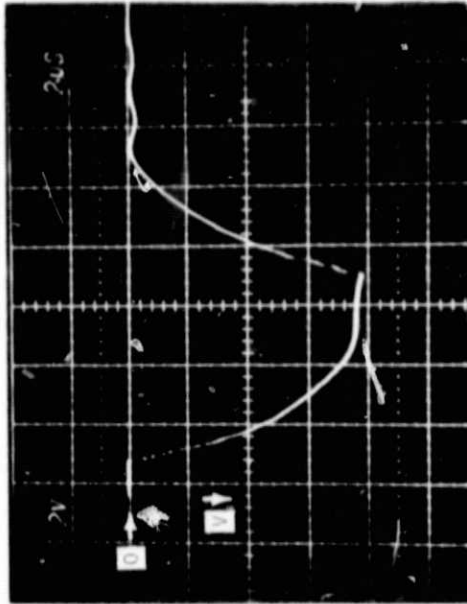
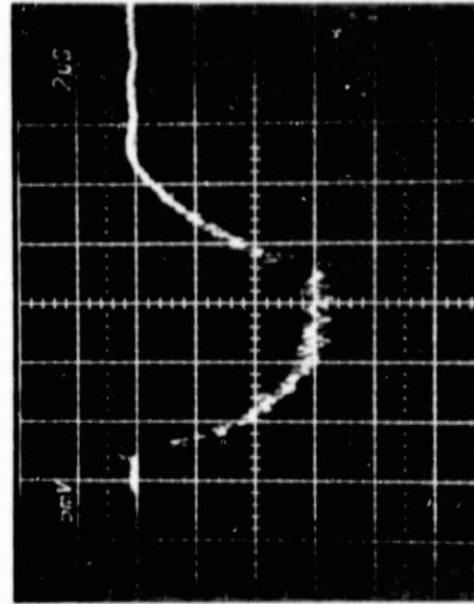


Figure 2. - Exploded view of electro-optic probe.

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(a) PROBE INPUT FOR WIDE INPUT PULSE (MEASURED WITH 1320-1 CAPACITIVE DIVIDER).



(b) PROBE OUTPUT FOR WIDE INPUT PULSE.

Figure 5. - Typical traces for dynamic response.

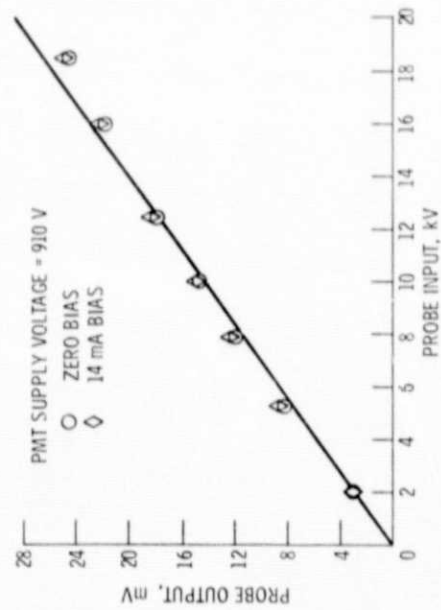
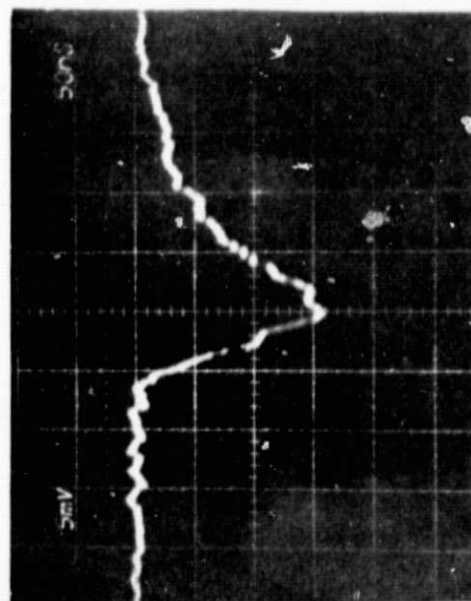


Figure 4. - H. V. probe calibration curve.

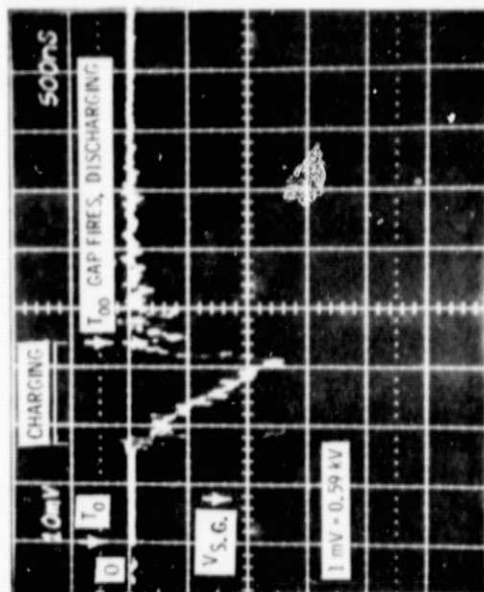


(c) PROBE INPUT FOR NARROW INPUT PULSE (MEASURED WITH 1320-1 CAPACITIVE DIVIDER).

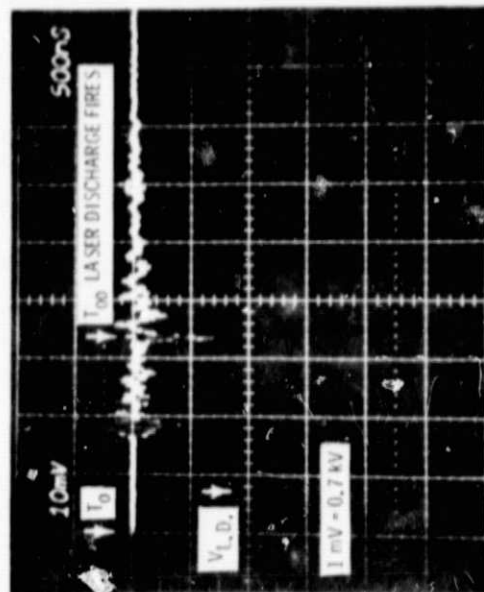


(d) PROBE OUTPUT FOR NARROW INPUT PULSE.

Figure 5. - Concluded.



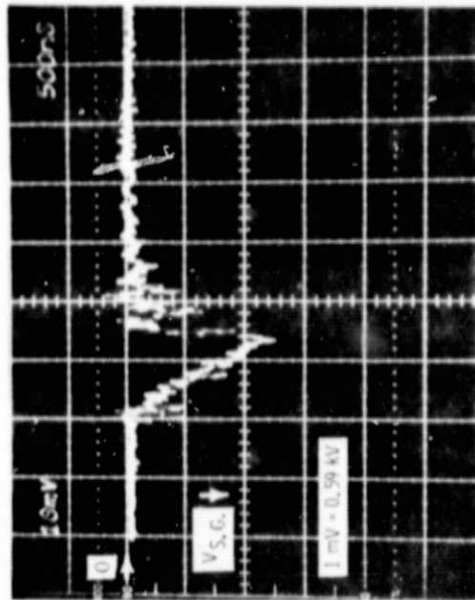
(a) SPARK GAP VOLTAGE, SLOW SWEEP.



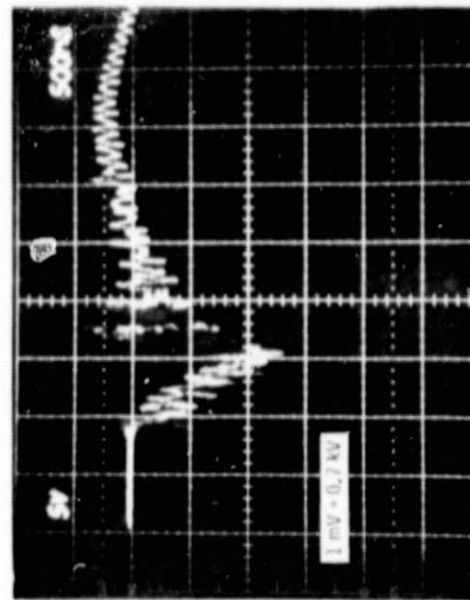
(b) LASER DISCHARGE VOLTAGE, SLOW SWEEP.

Figure 6. - Fast discharge waveforms obtained with new probe.

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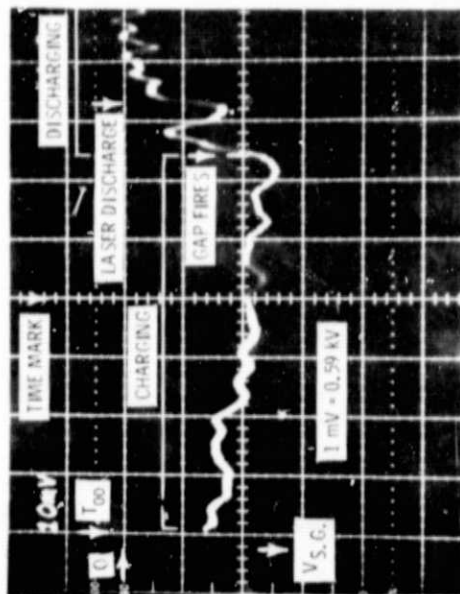


(a) NEW PROBE SYSTEM, SLOW SWEEP.

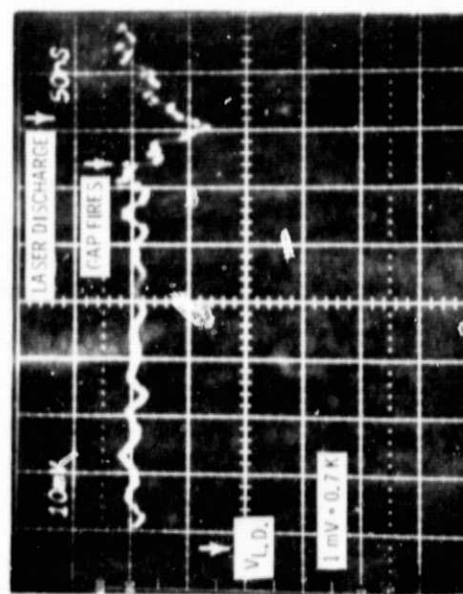


(b) COMMERCIAL PROBE SYSTEM, SLOW SWEEP.

Figure 7. - Spark gap voltage, comparison of probe systems.



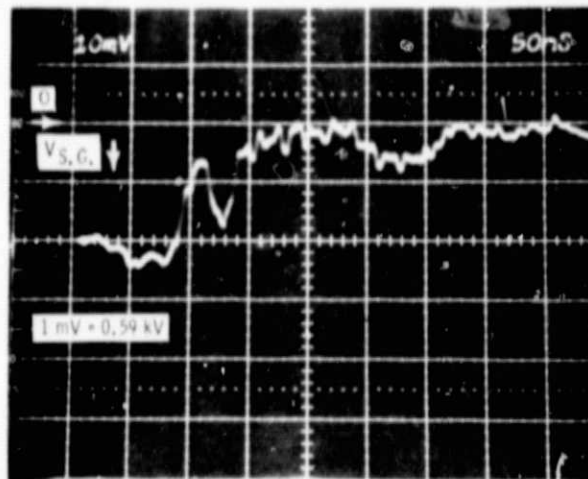
(c) SPARK GAP VOLTAGE, FAST SWEEP.



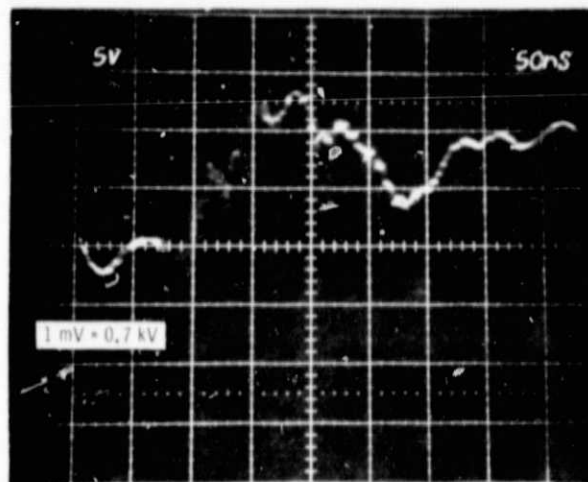
(d) LASER DISCHARGE VOLTAGE, FAST SWEEP.

Figure 6. - Concluded.

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(c) NEW PROBE SYSTEM, FAST SWEEP.



(d) COMMERCIAL PROBE SYSTEM, FAST SWEEP.

Figure 7. - Concluded.